ASTRONOMY

Odd-Shaped Pieces Confuse Puzzle of Galaxy Evolution

Astronomers hoped distant images would clarify how galaxies grow and change, but the big picture still hasn't come into focus

What fossilized shells and bones are to the history of life, galaxies are to the history of the universe. Astronomers have collected galaxies in great variety and numbers: ranging from newborn to elderly, dim to brilliant, shapeless to orderly, at distances as far back as anyone can see. With large enough collections, cosmologists once hoped, they would see the galaxies falling neatly into a straightforward history leading from clouds of gas in the early universe to the familiar, orderly spirals and ellipticals of today. Evolutionary biologists could have told them it wouldn't be that simple.

Even a few years ago, scientists had studied only a handful of galactic specimens. But recently, galaxy collections have grown flourishingly. Using new detectors that operate at infrared and submillimeter wavelengths, along with the Hubble Space Telescope's (HST's) two Deep Field views of the early universe, cosmologists have turned up exotic fossils: distant ultraviolet balls and nearer little blue messes, all forming stars at rates that range from moderate to vigorous; huge, smudgy, red galaxies forming stars so furiously that they give off a good fraction of all the light in the universe.

The distant galaxies' properties are still uncertain, their masses and exact shapes mostly a mystery. Cosmologists now don't know whether they are dealing with closely related creatures, or whether they are trying to construct an evolutionary history from cows, rattlesnakes, and squid. "We don't know whether we're looking at different populations or at one population in different ways," says Simon Lilly of the University of Toronto. But cosmologists are undismayed: "It's a big zoo out there," says Mark Dickinson of the Space Telescope Science Institute (STScI) in Baltimore, Maryland, but "it's a zoo with some order, and we're trying to piece it together."

Ill-fitting pieces

A generation ago, the pieces seemed to fit. Most cosmologists believed that galaxies were born large and fully formed and have simply ticked along quietly ever since, fading as they aged. In that case, early galaxies should be bigger and brighter than present galaxies, but otherwise they should look much the same. The problems began when astronomers started to see regularly beyond a distance they call z = 1. The "z" is redshift, the extent to which light has been stretched to longer, redder wavelengths by the universe's expansion. Galaxies ride the expansion; the farther away a galaxy is, the faster it is receding from us, and the redder its light becomes. Ultraviolet light turns optical, visible light becomes infrared, infrared light stretches toward the radio spectrum. Because reddened, distant light is older light, astronomers also invoke redshift to measure time. At z = 1 they are looking halfway back to the big bang; at z = 3, 84% of the way back; at z = 5, 91%.

Stodgy. Viewed in optical wavelengths, Lyman break galaxies such as this one (redshift 3.368) look like "not very interesting ... little balls."

CREDIT: STSCI/NASA/AURA

Ten years ago, z = 1 was as far as astronomers could easily see. But in the 1990s, a new technique opened up legions of increasingly distant galaxies, picked out by a feature in their spectrum called the Lyman break. Hydrogen atoms scattered through space between those galaxies and our telescopes absorb the ultraviolet light in a galaxy's spectrum, producing a sharp drop-off, or break, in certain wavelengths. By looking for this Lyman break, astronomers can pick out the light from galaxies shining when the universe was maybe a billion years old. The redshifts of Lyman break galaxies are scattered between z = 2 and 5.6.

Charles Steidel and colleagues at the California Institute of Technology in Pasadena, who were among the first to put this technique to work, have now collected nearly 900 Lyman break galaxies. In general, Steidel says, the Lyman breaks are "not very interesting—sort of like little balls, relatively small." But Steidel's team was looking at optical wavelengths. Corrected for redshift, that light had originated in the ultraviolet—the wavelengths of forming stars. Because stars form in isolated clumps within a galaxy, cosmologists suspected that the ultraviolet might be giving a distorted view of the distant galaxies' appearances. To see the true shapes of any galaxies at such large distances, cosmologists needed to look in the galaxies' own optical range: our infrared.

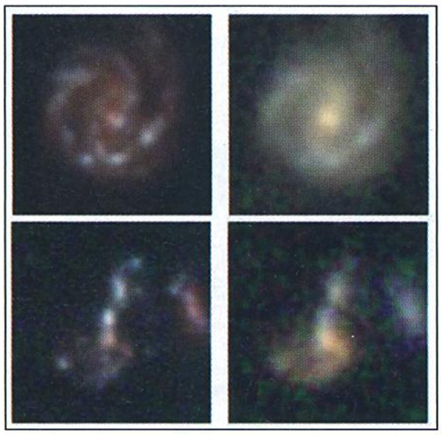
One hotbed of distant galaxies is the spectacularly beautiful Hubble Deep Fields, a pair of 10-day exposures of small areas in the northern and southern skies that STScI produced in the late 1990s. In 1999 several teams observed both Deep Field regions with a new infrared camera on the HST, called the Near-Infrared Camera and Multi-Object Spectrometer, or NICMOS.

One team—Hyron Spinrad and Andrew Bunker of the University of California, Berkeley, and Rodger Thompson of the University of Arizona, Tucson—compared optical and infrared images of the 100 brightest galaxies in Deep Field North. At redshifts around 2 and 3, Spinrad says, the galaxies even in their own optical wavelengths showed a range of peculiar shapes: "automotive accidents, bow shocks, multiple components." But "things clean up" around z = 1, he says. "There's a trend toward symmetrizing."

Dickinson, leader of a team now painstakingly comparing the optical and infrared images of 250 Deep Field North galaxies from redshifts 0.5 to 3, says his preliminary results confirm the trend. "Out to redshifts of 1, we have no trouble finding giants, normal spirals, and ellipticals. But over redshifts of 2, whatever these things are, they don't look normal." His conclusion: "You're not being fooled by the wavelength you're looking in. They really are disturbed systems."

Meanwhile, astronomers observing even longer wavelengths have found a new population of galaxies previously hidden in dust. Dust in galaxies absorbs the ultraviolet and optical starlight, heats up, and reradiates the energy as infrared light. The light of galaxies at high redshifts gets stretched into so-called submillimeter wavelengths, between infrared and radio. In late 1996, several international teams used a camera called SCUBA (for Submillimetre Common User Bolometer Array) on the James Clerk Maxwell Telescope in Hawaii and found a handful of surprising galaxies with redshifts between 1 and 3.

The submillimeter galaxies aren't numerous—in an area of the Hubble Deep Field with hundreds of galaxies, SCUBA finds just five—but they are outrageously bright. By calculating how much starlight would be necessary to heat dust to the energies they observe, astronomers have concluded that each submillimeter galaxy is forming stars at least several hundred times faster than our galaxy does. Taken all together, says Toronto's Lilly, who is on one of the teams, this small class of galaxies "has produced a significant fraction of all the light in the universe."



Spiffy. Galaxies at redshifts near 1.0 *(top)* tend to be more symmetrical and orderly than those at redshifts around 2.0 *(bottom)*. Images at left are optical; at right, infrared.

CREDIT: (TOP AND BOTTOM) STSCI/NASA/AURA

Dusty picture

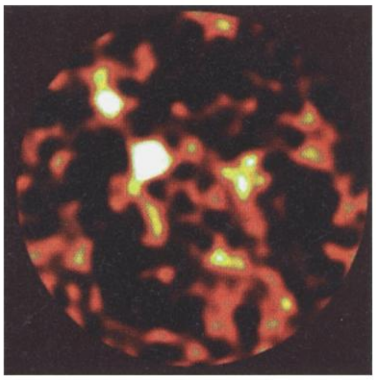
To make sense of all these multifarious galaxies, cosmologists must try to fit them into a larger evolutionary picture. In the most popular scenario, known as hierarchical formation, the first galaxies to condense out of primordial gas clouds are small disks. The disks can merge and form brilliant galactic cores, called spheroids. Some spheroids probably become elliptical galaxies; others pull the ambient gas into disks and become spirals. Nearby galaxies may collide, igniting frenzies of star formation, then settle slowly into ellipticals. Later still, and slowly, smaller gas clouds light up with stars, merge with other gas clouds, or fall into nearby galaxies. In this violent, almost biologically messy process, astronomers would expect to see increasing numbers of merging galaxies with increasing distance.

But exactly where do the distant observations fit into the scenario? "There," Steidel says, "you're on thin ice." For one, although the submillimeter galaxies are certainly bright enough to be the results of mergers, no one knows whether they have the messy shapes of galactic wrecks or the symmetry of spheroids: SCUBA's resolution is so low that they look like big red smudges. Accordingly, matching a submillimeter galaxy to its optical counterpart is an exercise in probability. "At the start, we all had a tendency to pick something [on the optical map] faint and close to the right position, and say, 'That's it,' " says Ian Smail of the University of Durham in the United Kingdom, a researcher on one of the teams.

Recent follow-ups with the Keck Telescopes and HST, coupled with high-resolution radio observations, have assigned fairly believable optical counterparts to at least half of the submillimeter galaxies. Those observations suggest that the submillimeter galaxies most closely resemble a small, local class of galaxies called Ultra-Luminous Infrared Galaxies—more elegantly, ULIRGs or ULIGs. ULIGs are ultrabright, ultradusty objects that most likely occur when galactic mergers set off a violent burst of star formation. "To the first order, I reckon all these objects are similar to ULIGs," Lilly says. "I don't know of any properties that are different."

In any case, astronomers suspect that the submillimeter galaxies are transients. "We only see them when they have the awful accidents of merging and turn into spectacular firework shows," says Len Cowie, an astronomer at the University of Hawaii, Honolulu. Smail says he thinks of them "as an event rather than as a galaxy."

Similar disputes arise over Lyman break galaxies. At redshifts between 2 and 4.5, the faint blue blobs could be almost anything. Because Lyman breaks cluster the way today's big galaxies do, STScI's Dickinson says, "we'd sort of like to say that Lyman breaks turn into spheroids." If so, then some of them, at least, could be the same sorts of objects as the submillimeter galaxies, only viewed at different wavelengths.



Smudgy. Submillimeter images taken by the SCUBA camera (here, the Hubble Deep Field North) are hard to match up with optical sky surveys.

Steidel thinks that is possible. Lyman breaks "have a huge range of luminosities, maybe a factor of 100," he says. "It's a continuum of dustiness and luminosity, and [SCUBA is] seeing the dustiest and most luminous." But Cowie thinks another step is necessary to boost the Lyman breaks to high energy. "I don't at any level think the submillimeter objects are just the bright-end flavor of the [Lyman] break galaxy population. It's when Lyman breaks merge to form spheroids that we get the bright submillimeter population."

Needed: more pieces

What's needed to settle the debates is—as usual—more data. Astronomers need to know the galaxies' true shapes and their interior motions, from which they can calculate the galaxies' masses. The Next Generation Space Telescope is designed for just those kinds of observations. New infrared and submillimeter observatories are in various stages of planning; in particular, the Millimeter Array, an interferometer to be constructed in Chile within the next decade, will see much more detail than SCUBA can.

Until they can make those detailed observations, some astronomers are taking a more impressionistic approach to galactic evolution by measuring how the total rate of star formation throughout the universe has varied over time. To measure this cosmic life force, says Piero Madau of STScI, "you count the galaxies, measure their light, convert the light to a star formation rate, [and] bin it up by redshift space."

In the past 2 years, such measurements have been made in ultraviolet, optical, infrared, and submillimeter wavelengths. All show roughly the same trend: The star formation rate is low at present, rises as you go back in time, then levels off and remains high as far back as anyone can see. In other words, the early universe was alive and jumping. Then, says Princeton cosmologist Jim Peebles, it gradually "ran out of gas and is now just living off its remittances." The drop-off point: a redshift around 1, about when most galaxies seem to have settled into symmetry.

Exactly what the cosmic star formation rate implies about galaxy evolution, no one knows. At the least, the rate sets a rough history of the universe as a system, says Lilly, who helped invent the idea. "We've been trying for donkey's years to understand formation and evolution of galaxies," he says, "floundering around in a morass of Lyman breaks and submillimeter galaxies. If you're interested in the universe as a system, all these little galaxies might be something of a nuisance."

–ANN FINKBEINER

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